# Design of An Interactive Lumbar Puncture Simulator With Tactile Feedback

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## 1 Introduction and Background

Lumbar puncture for purposes of administering spinal or epidural anesthesia is a complex clinical skill which requires the clinician to precisely correlate a detailed mental map of hidden three-dimensional anatomy with tactile feedback from the spinal needle as it's being inserted. Currently, this procedure is taught to students and/or residents using a process of supervised trial-and-error on real patients. The objective of this project is to develop an improved method of teaching this skill using a computer-based interactive simulation with sophisticated real-time 3-D graphics and integrated tactile feedback. Learning to perform lumbar puncture for spinal and/or epidural anesthesia is currently a stressful and inefficient experience for the student (and supervisor!) as well as an often painful and potentially dangerous experience for the patient. Other fields, such as aviation, have demonstrated the utility of realistic simulators for safely and efficiently teaching similarly complex and dangerous skills like flying an airplane .

Systems have been described which simulate various aspects of anesthesia including the O.R. task environment monitoring, general anesthesia, critical incidents, fiberoptic intubation, pharmacokinetics and pharmacodynamics, continuous infusions, uptake and distribution of inhaled anesthetics, cardiopulmonary bypass, and epidural injection. Many of these systems have been computer-based, some have included mannequins, and some have attempted to physically duplicate the O.R. The overall conclusion has been that these simulations have been very useful in improving trainee success rates.

With one exception, no simulations have been described for regional anesthesia in general and lumbar puncture in particular. All major regional anesthetic techniques share the requirement of precisely placing a needle into or near deep anatomic structures which are only indirectly located by surface or bony landmarks. To be successful the trainee must create a mental map of the anatomy by integrating atlas illustrations with bony and/or surface landmarks. The placement of the needle must then be guided by the continuous correlation of this mental map and the tactile feedback, or "feel," of the needle as it is being inserted. Lumbar puncture for spinal or epidural anesthesia shares these characteristics. At Dartmouth, a collaborative work between the engineering and medical schools is attempting to address these issues. The hypothesis of this project is that a computer-based simulation utilizing high-resolution 3D graphics and a force-feedback device to simulate the "feel" of inserting the needle can be developed, and that once developed it can be used to more effectively train students and/or residents in this technique.

The simulator consists of a combination of specialized hardware and custom software running on a high-resolution graphics workstation. In this paper, we describe the hardware we are

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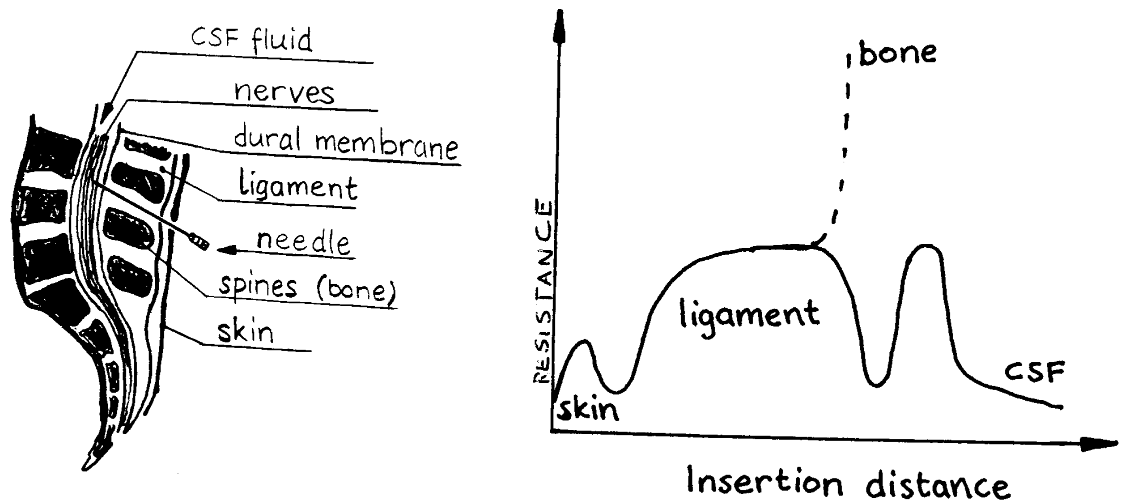



Figure 1: (a)A cross section of the spine; sketch made from [1] and (b) Curve of resistance encountered when inserting a spinal needle.

developing for this project. The major piece of specialized hardware is the force-feedback needle simulator. This is a specialized joystick which resembles a long, thin pen or wand swivel-mounted to a vertical face of a box roughly 12 inches on a side. Position sensors track the insertion angle or trajectory of the device while a programmable motor or actuator will provide variable resistance to insertion depending upon which simulated anatomic structures the virtual needle is penetrating. Thus, the student may place the virtual needle at the desired angle and will feel realistic resistance while inserting. If an incorrect trajectory is used and bone is contacted the resulting sudden sharp increase in resistance would be conveyed.

## 2 Description of the needle insertion procedure

A brief description of the needle insertion procedure in spinal anesthesia is given below:

- The needle, which is like a steel hose has outside and inside diameters of approximately 0.6 and 0.3 mm. The length of the needle is about 90 mm. Inside the needle is a stiletto which can be pulled out after insertion to get the fluid in or out.
- The patient can be in a sitting position on a chair or lying on his/her side on the bed. In both positions the patient must be lying in a curled position. This separates the spine, (see Fig. 1a).
- The insertion is made at a specific angle $\alpha$ depending on the anatomy of the spine, where $\alpha$ varies between 0 and 30 degrees. Once the needle goes through the skin it is held at the same angle by the dense ligaments (see Figure 1a).

As can be seen from Figure 1a the needle has to enter with precision between the bones into the fluid filled sac. When inserting the needle, the resistance force varies depending on the depth of penetration and the insertion angle $\alpha$. For a specific $\alpha$, the resistance could be as shown in Figure 1b.

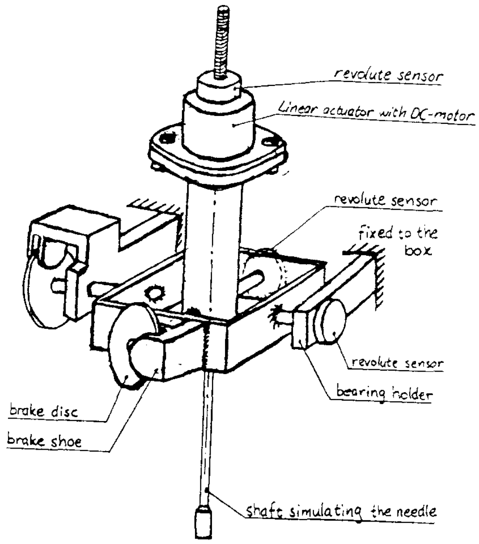



Figure 2: A schematic view showing the interior of the box with the principal mechanical components and sensors

## 3 Conceptual Hardware Design

Figure 2 shows a schematic and Figure 3 shows an actual picture of the hardware we have built; a box with vertical sides and a joystick attached to it simulates the system. The joystick has three degrees of freedom- two are rotational and a third is translational.

The box contains the mechanical equipment for accomplishing the following major objectives as shown in Figure 2.

*Freedom of movement*

The mechanical joint should allow the needle to move freely in a solid cone of at least $60^0$, because the real needle insertion is done within this angular range.

*Measurement of needle orientation*

To measure the orientation of the needle, sensors must be mounted to the joint. Requirements for measuring the orientation are:

- Measure all angles within the $60^0$ cone, as discussed earlier.
- Resolution of about 565 counts/rev. With 90 mm of the needle inserted it should be possible to have a resolution of about 1 mm on top of the needle. This gives 565 counts per revolution for the encoder.

*Measurement of needle position*

Another sensor must measure the insertion depth of the needle. The position accuracy should be at least $\pm 0.5mm$.

*Force feedback*

Force feedback along the needle direction is provided by a linear actuator. This actuator must be able to push and pull with a force of at least 10 N. The reason for choosing 10 N is to have some safety margin with respect to the buckling strength of a real needle, which is estimated to be 7 Newtons. The minimum force encountered when inserting the virtual needle should be smaller than 0.5 N This is the approximate magnitude of the smallest force acting

on a real needle, during insertion. Further, the actuator should also be light since it will move with the needle in order to maintain alignment, producing a force only along the length of the needle.

*Lock of needle orientation*

The needle orientation should be fixed by a lock mechanism when the insertion begins. This is to properly simulate the dense ligaments (see Figure 1a) which resist any changes in the needle orientation after that the needle has penetrated a certain distance. The lock mechanism should have the following features:

- Continuous and able to fix the needle at any orientation.
- Transfer a torque of at least 0.45 Nm. ( A force of 10 N acting on the end, perpendicular to a half inserted 90 mm needle.)
- Electrically powered.

# 4 Design details

*Open Centered Universal Joint*

To make the needle freely movable within a $60^0$ solid cone a universal joint, which consists of two orthogonal axles, has been chosen because it enables easy measurement of the orientation by simply mounting an angular sensor on each axle. A problem encountered was how to make the needle go through the joint. For this purpose the Open Centered Universal (OCU) Joint has been developed (see Figure 2). This enables the linear actuator to be mounted to the joint and the linear actuator shaft (needle) to go through the joint.

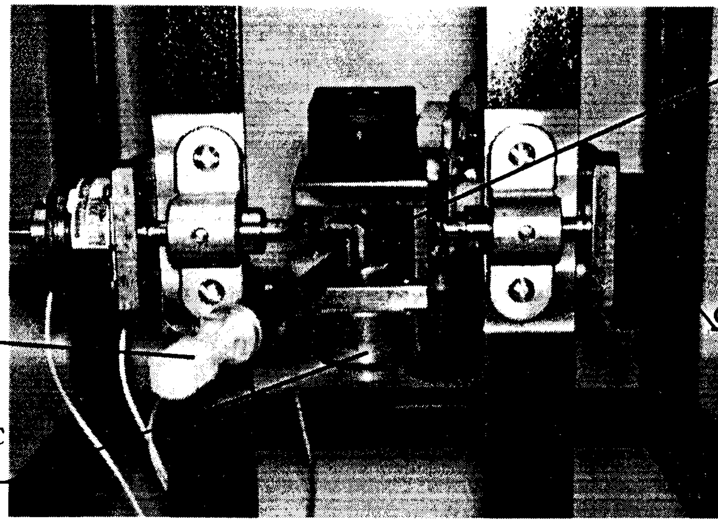
*Sensors*

To monitor the needle orientation an optical encoder has been mounted on each axle. Modular optical encoders with a resolution of 500 pulses per revolution (ppr) have been chosen. This gives a resolution of $0.72^0$ which is equal to 1.1 mm at the end of a 90 mm long needle. This is close enough to the 1 mm requirement. The linear position of the needle must also be measured. This is accomplished using a revolute sensor mounted to the DC - motor. The pinion mounted on the DC - motor has a pitch diameter of 6 mm, which gives a linear resolution of 0.038 mm. This is much better than the required 1 mm.

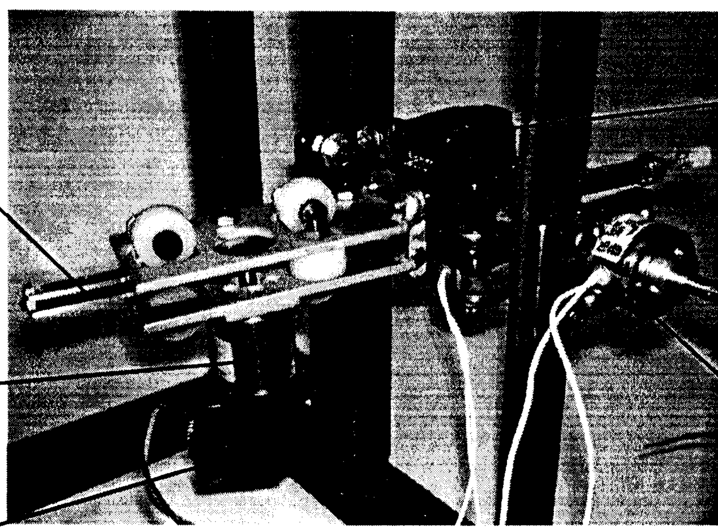
*Linear actuator*

This is a critical part of the design. First there must be some mechanism which can move linearly through at least 90 mm. Further it must be driven by a motor to actually produce the force feedback. This must be able to push and pull with a force of at least 10 N to simulate the interior anatomy. The force and the position of the linear actuator must also be measured by sensors. The whole unit should also be very light (max. 500 g) because this unit will be mounted on the OCU-joint and will move with the joint when the orientation of the needle changes. Therefore a linear actuator with a rack and pinion was developed. The main parts are made of aluminum to decrease the weight. The rack slides between nylon wheels to reduce the friction. The first approach is to try plain nylon wheels. If friction is still a problem, roller bearings will be added. The motor also has low friction torque, which is important to keep the minimum friction thrust force below the required 0.5 N. The friction torque gives a thrust force of 0.0012 Nm / 3 mm = 0.4 N, which is lower, but there is additional friction between the rack and the nylon wheels.

Figure 3: THE HARDWARE FOR SIMULATING LUMBAR PUNCTURE




FRONT VIEW




A VIEW FROM INSIDE THE BOX

*The lock mechanism*

In real insertion the needle enters the dense ligaments immediately after penetrating the skin (Figure 1a). This means not only that the resistance in the needle direction is higher, but also that it is not possible to change the needle direction once these ligaments are entered. To simulate this fact there must be something that locks the needle orientation when it has been inserted to a certain depth (0 - 2 mm). For doing this there must be a mechanism that can lock the two joint axles of the OCU - joint. This has been accomplished by mounting electromagnetic brakes on each axle.

*The force transducer*

The hub of the needle has been instrumented with a force transducer. This is a cantilever beam with strain gauges mounted on it. The force on the needle induces a corresponding linear strain in the strain gauges. An electronic circuit amplifies and filters the signal and produces a voltage directly proportional to the force, which is then used as the measured output in a feedback control module. Details of the force sensor may be found in [4].

# 5 Software Development

The software for this project consists of an accurate, high resolution, three-dimensional digital model of the normal human lumbar spine with surrounding soft tissues, ligaments, and skin. This model is derived from actual MRI data to allow extreme accuracy. Display and control modules have been written which allow the model to be realistically displayed in 3D. At this point, we are displaying the graphics on a Silicon Graphics Personal Iris machine. In the future we may make use of commercially available devices which allow the viewing of a true 3D image on a flat computer display screen as well as allowing the computer to track the head position of the user and appropriately adjust the display in response to the user's head movements. The resulting 3D image is very convincing. In addition the control logic must follow the position of the virtual needle, display the needle as it is inserted, and simultaneously exert appropriate resistance to the needle's insertion. The transparency of the skin and soft tissue layers will be variable by the user.

# 6 Hardware architecture

A two-tiered control and supervisory architecture has been developed for this research as shown in Figure 4. The "low-level" microprocessor board contains the necessary electronics to collect digital data from the optical encoders, analog data from the force sensor and the control program to apply the necessary control force through the DC motor. We are currently investigating several novel adaptive force control and adaptive impedance control schemes to increase the effectiveness of the force feedback [5].

The board communicates through a serial port to the Silicon Graphics Iris within which reside the software modules for displaying 3D model of the spine and the position and orientation of the needle superimposed on this model.

# 7 Future Potential

This project holds great potential for further investigations. Successful demonstration of this simulator opens the possibility of extending the concept to other procedures and anatomic

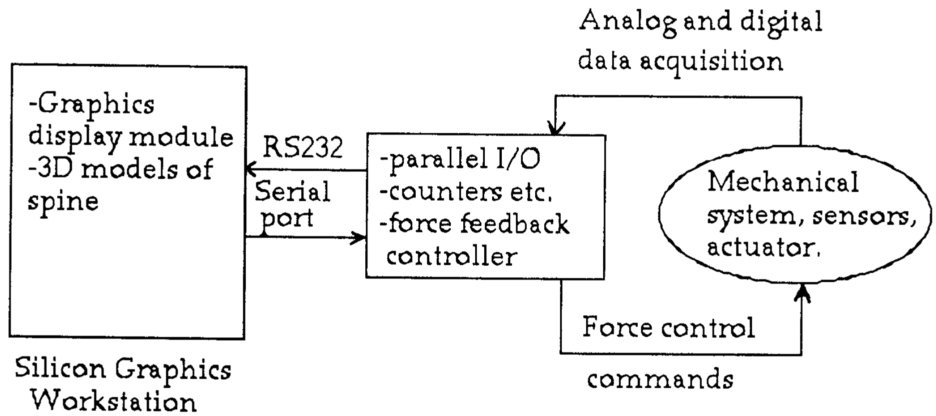



Figure 4: The two-tiered organization for the control and display of the lumbar puncture simulator

areas. Other regional anesthetic techniques which could be simulated include brachial plexus blocks, stellate ganglion blocks, and cervical plexus blocks. Similarly various vascular insertion techniques could be simulated. These might include central venous and/or pulmonary artery cannulation via the internal jugular or subclavian approach. Only the software need change, the hardware would be applicable to any of the above possibilities.

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